OPTICAL CORRELATION TECHNIQUES

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by

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ABSTRACT

The design of a radiometric experiment is described which provides a laboratory model for implementation of the optical correlation technique. The radiometer has provision for alternately viewing the source directly and through a gas absorption cell. The source may be characterized either by unstructured continuum or by specific molecular emission. Optimization of the gas cell parameters (temperature, pressure, etc.) is sought for maximum discrimination between molecular and blackbody emission. The cell is 10 centimeters in length and may be operated up to two atmospheres in pressure. A double pass may be made by the replacement of one end window with a mirror. The detector bandpass is limited by optical filtering. The desirability of an advanced molecular absorption band model for highly non-isothermal paths and further absorption-emission spectraradiometric data are discussed.

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SECTION I

INTRODUCTION

The current program ultimately involves the application of molecular gas filtration techniques aboard operational satellites to improve the SWIR detection and discrimination capabilities of existing and future systems, particularly as regards target observation in the 5-10 km lower altitude region. The fundamental molecular gas filtration scheme involves obtaining a correlation ratio between an unfiltered and a filtered field of view. Inasmuch as target signals can be attributed to emissions from distinctive constituent species such as H_2O, CO_2, HCl, etc. which radiate characteristically in emission bands, the insertion of a molecular absorption path with a relatively high optical depth ($\tau > 1$) of the same gaseous species will provide significant signal absorption. Alternatively, the normal background and abnormally high backgrounds attributable to solar reflection from high altitude clouds is principally unstructured continuum. As a consequence, insertion of a molecular absorption cell will produce only a minor decrease in background. Thus, utilization of the gas absorption filter under conditions when a signal is present under normal or high background conditions tends to increase the system signal to noise ratio by providing distinctive ratios between filtered and unfiltered observations.

In order to capitalize most effectively upon this scheme, a laboratory program is under construction to model the situation as accurately as possible. Additional information is required as to the emission-absorption characteristics of water vapor, the gas selected for the initial experiments. Considerable data exists on water vapor spectra, but unfortunately it is not generally possible to utilize this information in detail to yield the required results over the highly non-isothermal paths involved. Furthermore, since it is impractical to use other than an ambient pressure flame in the laboratory, a computational model is desired to extend laboratory data to relatively unobtainable parameters. These will include lower pressures, more widely variable temperatures, and greater optical path lengths.

These various aspects of the problem are discussed in the following sections. The spectral data required principally will enable the optimum spectral bandpass to be selected without extensive trial and error procedures. A computational model will allow extension of data to other parameters and the laboratory program will provide basic data on the technique and experience vital to the design of full scale experiment.

SECTION II

MOLECULAR EMISSION/ABSORPTION DATA

As mentioned above, although considerable data exist on water vapor spectra in the 2.7 μm band, this information is not generally applicable to the present problem. An experimental setup is operational at the Environmental Research Institute of Michigan (ERIM) which may yield valuable spectroscopic measurements.[1] Simulation of signals may be accomplished at ERIM employing a heated cell up to 60 cm in length that may be operated at temperatures up to 1200°K at pressures between atmospheric to the vacuum region. Gas mixtures with various partial pressures may be accommodated. Conversion to HF or HCl would require alternative materials for some of the components. Signals may also be simulated by burners. At ERIM, diffusion burners, in which the gases mix at the flame front, are employed to provide a stable flame with no blowback. Stability is affected by the temperature of operation. In the case of an H_2 and O_2 flame, the temperature range of stable operation is between about 2000°K to 2600°K. Temperatures down to 1500°K may be obtained by gas dilution or the replacement of some H_2 by hydrocarbon. In this latter case, however, some CO_2 is produced which also has a major absorption band in the 2.7 μm region with its obvious attendant difficulties. Gas temperature is measured in these flames by the sodium line reversal method. The dimensions of typical burners are about 1-inch square, and a reasonably uniform temperature zone is located at about 1 inch above the burner. Burners of the same type have been constructed up to about 9 inches in length.

The experimental apparatus has provision for switching a cool gas cell into the optical path. The cell is 10 meters in length and by the use of multiple passes may be made up to 200 meters in effective length. The cell can only be operated at ambient room temperature and thus the water vapor pressure cannot exceed about 15 mm Hg or about .02 atmospheres pressure. Other gases may be added up to atmospheric pressure.

The radiant emission from the hot cell or burner can be made to pass through the cool cell prior to spectrophotometer or radiometric detection.

Unfortunately, however, no provision is available for viewing alternately as is planned in the current work, nor would it be possible easily to provide it.

Preliminary data taken with the following parameters shows some correlation discrimination of the hot cell radiance:

	Hot Cell	Cold Cell
Temperature	1201°K	296°K
Length	60 cm	10,000 cm
Pressure H_2O	.05 Atm	.001 Atm
Pressure N_2	.05 Atm	.069 Atm

The transmittance of the cold cell for continuum radiation is 0.84 in contrast to 0.50 for the hot cell emission. This is a favorable result, considering the fact that since the experiment was performed for a totally different purpose, no deliberate optimization of cell parameters was considered.

Since in an operational surveillance system, such a large number of multiple passes is not likely to be possible, nor is the prohibitive cell length of 10 meters, the principal thrust of effort is to be directed toward obtaining equivalent or better results with shorter absorption cell paths.

The ways this may be accomplished include: raising the absorption cell temperature, in order to raise the attainable vapor pressure of water. Care is necessary to prevent self-emission from the absorption cell from making a significant contribution to the radiance. Water vapor at 180°C has a saturation vapor pressure of about 10 atmospheres, thus the equivalent optical path of 10 atm. cm from the above-mentioned data can be met by one centimeter path length.

A further consideration involves optimization of the line broadening parameters. Since pressure broadening is dominant in the operational regime, the best initial optimization would be to operate the cell at the same pressure as the signal. In the case of the laboratory program, this

would mean atmospheric pressure, and for water (with no foreign gas) the temperature will be 100°C. For optimum surveillance, the pressure should be that of the plume at the lowest altitude at which detection and discrimination are expected, yielding pressures in the range 0.25 to 0.5 atmospheres and cell lengths in the range 20 to 40 cm.

SECTION III

EXTENSION OF DATA TO NON-LABORATORY PARAMETERS

In order to extend data to be obtained from the laboratory correlation experiment to a range of parameters unobtainable in the laboratory, a suitable computational model is required. Extensive effort has been applied to the solution of the problem of modelling water vapor emission/absorption spectra. While exact calculations are possible, they are prohibitively costly, owing to the extreme complexity of the spectra. This complexity arises because of the fact that the water molecule is a non-linear trinuclear molecule with low symmetry and widely differing moments of inertia along its principal axes. The 2.7 μm band is primarily a vibrational band but the levels are rotationally split. This gives rise to very large numbers of transitions. In this band there are about four spectral lines per wave number at 2000 K and the current interest extends over several hundred wave numbers. In order to calculate radiance, absorption and so on, band models have been developed with varying degrees of sophistication. It is easily seen that in order to compute parameters for the current problem, a wide range of input parameters is required. In the simplest case derived from the laboratory, a two-layer water vapor model is required. The flame is a thin (but not very thin) quasi-isothermal source of water vapor spectra. Self-absorption may be neglected as may the intervening space in the laboratory. The cell is a cool isothermal source of very substantially different temperature. Here the self-emission may be neglected provided temperatures are not above ambient. It is seen that even in this case a mathematical model must attack the problems of highly non-isothermal paths, partial line overlap, non-linear curve of growth, absorption and emission by the same molecular species. In extending the modelling to a system involving a plume, one must add to this the highly variable and rather little known temperature distributions within the plume as imaged on a detector element, the absorbing contribution of both water vapor and carbon dioxide over variable slant paths through the atmosphere.

Extensive effort has been directed to providing an accurate self-consistent solution to this problem in the past decade. Data is available (e.g. 2) for some engineering purposes but does not generally include sufficient refinement to enable good evaluations of the expected correlation ratios to be found in the laboratory experiment. In particular, the significantly different effect of a cool absorbing gas on the transmittance of specific iso-molecular gas emission versus continuum radiation cannot be computed. In order to broach this problem, a more sophisticated model has been developed.[3]

The model begins by investigating the curve of growth of a single collision broadened spectral line along a non-isothermal path. The radiance of a single isolated spectral line from a non-isothermal source, assuming local thermodynamic equilibrium, no scattering and no other radiation source behind the emitting gas, is given by:

$$L_\nu(\nu) = \int_o^{X_L} L^*_\nu(\nu,X)\, k(\nu-\nu_o,X)\, \exp\left[-\int_o^X k(\nu-\nu_o,X')dX'\right] dX$$

This is the integral over the optical path X_L of the blackbody function L^*_ν times the absorption coefficient k times the exponential integral of the absorbtance to the point X. In following this calculation through, it is found that integrals over X and $\nu-\nu_o$ are generally not separable for non-isothermal paths. Various approximations have been developed to enable the separation of the integrals and replacement of the non-isothermal path by an equivalent isothermal path. Such computations require the introduction of an equivalent line width W. The width is, however, varying in such a situation, and a further complication is found in that a good approximation for W does not, in general, provide a good approximation for the derivative dW/dX along the optical path. A method of overcoming this problem has been derived which, however, requires extensive computation to yield the required values for band emission and absorption in the type of situation described above.

It is understood[4] that development of the computer code for these calculations is still ongoing, but may be available in the not too distant future. Furthermore, a seminar is planned at Aerospace Corporation to teach and discuss such computational methods for the solution of band emission/absorption. In the light of the foregoing, this aspect of the program awaits these external developments.

SECTION IV

LABORATORY PROGRAM

From the foregoing sections it can be seen that detailed spectroscopic information may most effectively be obtained from ERIM; thus, it is concluded that the laboratory program to be performed in the current contract will be most effective if a relatively simple radiometric correlation experimental apparatus is fabricated. The spectral extent over which correlation will be performed in any given experimental configuration will be determined by suitable bandpass filtering. Figure 1, which is derived from recent ERIM data[5], shows in curve a the spectral radiance of a hot water vapor source and in b the same radiance viewed through a cool cell. Correlation absorption is occurring where the curves are divergent. The bandpass filters to be used initially in the current work have half power points corresponding to (c-c) and (d-d). The former is approximately coincident with current surveillance systems and the latter appears to maximize the correlation for the particular conditions extant in the ERIM experiment. Alternative bandpasses will be used as information becomes available to enable their specification.

The laboratory program will provide simulated signals of the type encountered in an operational surveillance system. These may be divided into three broad categories. The background normally appears as a quasi-blackbody source at the temperature of the lower atmosphere. In the 2.7 μm band, water vapor and carbon dioxide are the principal emitters, but despite their strongly structured spectral emission, the optical depth is such that the emission is near blackbody even in nadir viewing. Very slight spectral structure is evident due to the differing thermal layers in the region below about 10 kilometers. This may be neglected however. The simulated background will be provided by black anodized aluminum at ambient laboratory temperature.

The target signal consists of gas and particulate emission at relatively high temperatures. Typical nozzle exit temperatures are in the range of

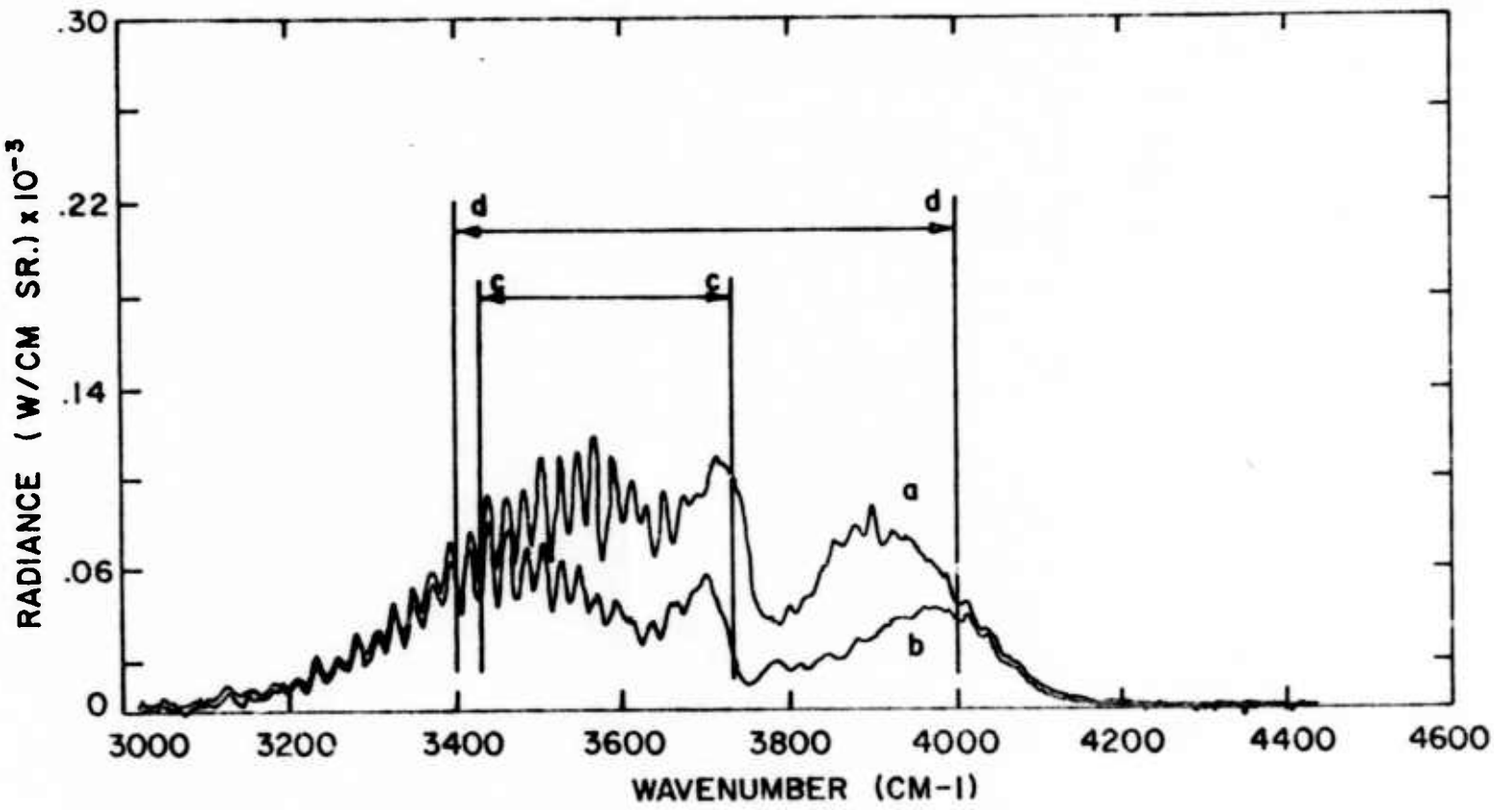

Figure 1. Observed Spectral Radiance vs. Wavenumber

a) of 60 cm hot cell containing 0.05 atm of water vapor and 0.05 atm of N_2 at 1201K.

b) of hot cell with same fill but viewed through the cold cell with 100 m path containing .001 atm water vapor and .069 atm of N_2 at 296K.

1600K. The emission downstream of the nozzle is a complex function of the fuels employed, the stochiometry of combustion, and hence the proportion of unoxidized fuel that may contribute to after-burning, motor size, amount and size distribution of particulate matter produced, as well as many additional subtleties including the possible quenching of after-burning by species such as hydrogen chloride. Commonly occurring hetero-nuclear (IR emitting) gases are CO_2, CO, H_2O, and HCl. Of these, H_2O has been selected as being both the most widely applicable and yet easily handled gas. Carbon dioxide, which also emits in the 2.7 μm band, offers some operational advantages in the absorption cell (see below) but is not present in significant quantities in some plumes of interest. Both CO and HCl have principal emission bands outside of current operational surveillance systems and hence higher backgrounds would offset possible gains. The laboratory simulated target has thus been selected as a hydrogen-oxygen flame. A commercial diffusion type burner has been selected with a nozzle diameter of about 2 cm. Since it will be operated in the laboratory at atmospheric pressure, the optical path of water vapor above the burner will be approximately 2 cm-atm. Although this is representative of the optically thin regime, one finds, somewhat surprisingly,[6] that target plumes may also be optically thin in water vapor emission. It is expected that the operational temperature of this flame will be in the range of 2000K. Dilution with an inert gas such as nitrogen will be resorted to, if necessary, to simulate more accurately the target temperature characteristics.

Potential false alarms occur due to solar-illuminated diffuse reflectors (i.e., principally clouds). This radiation is continuum in nature with the exception that atmospheric absorption by water vapor will occur to some extent. The simulated source to be utilized in the laboratory will be one or more 600 watt quartz halogen lamps reflected from a buffed aluminum plate. It is desired to obtain a radiance equivalent in intensity to the flame over the spectral band of interest. It may be necessary to employ a directly heated diffuse source such as a graphite rod.

The overall experimental layout is shown schematically in Figure 2. Radiance from either the flame or diffuse source arrives at the detector

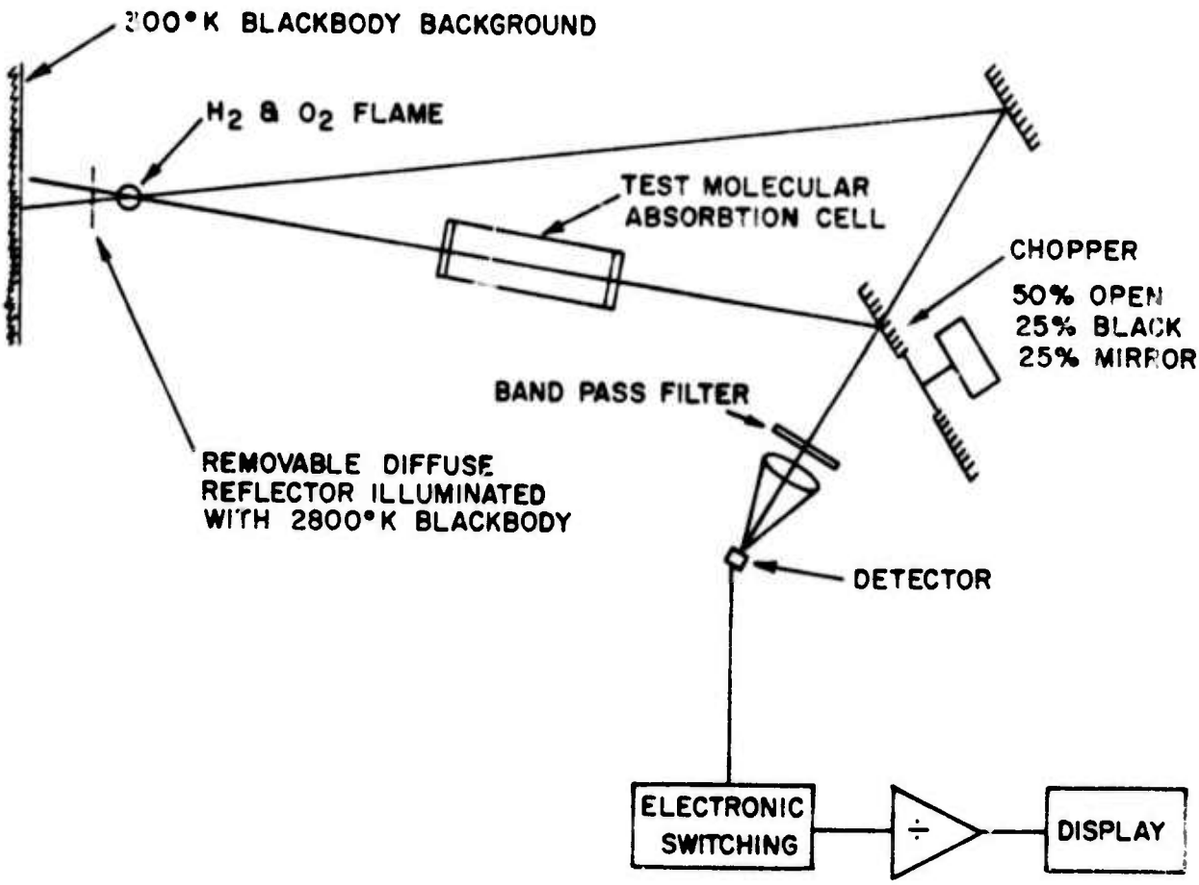

Figure 2. Schematic Diagram of Laboratory Layout

via two possible paths, as shown. These paths are selected by the chopper which is a specially modified model CTX-534 from Laser Precision Corporation. This chopper has two blades which are usually supplied black with 50 percent open area. The special modification consists of having one blade flattened and polished to form a mirror. Since only one blade is so treated, difficult alignment problems between several blades are avoided. The black blade provides a zero reference to the pyroelectric detector which is necessary in any case as it is a capacitative source and thus only the AC component is available at the output. The detector output will be switched synchronously with the chopper blade to separate the filtered and unfiltered signals and then divided to yield the ratio. Direct comparisons of the flame and the continuum signals will thus be possible.

The gas absorption cell has been constructed as shown in Figure 3. The body is of 316-grade stainless steel and windows of water-free fused silica (GE 125). The cell has been designed initially to operate with water vapor alone (no foreign gas broadening) and the pressure will be regulated by external heaters wherein the liquid and vapor will be in equilibrium. Design pressure extends over vacuum to two atmospheres, and pressure relief is incorporated in the event of accidental overheating. The cell length is 10 cm, and thus up to 20 cm-atm of water vapor path will be available. One of the windows may be changed to a suitable mirror, and the cell may then be doubled in length to yield 40 cm-atm of water vapor path.

As noted previously, carbon dioxide could be employed with a hydrocarbon oxygen flame. A significant advantage would be that similar pressures can be obtained without heating; indeed the cell may be cooled if desired. In order to maximize the correlation ratio in an operational system, multiple gases may be used. In that case, of course, a combination of water and carbon dioxide would be the most obvious choice owing to the spectral overlap of their bands with the current operational regime.

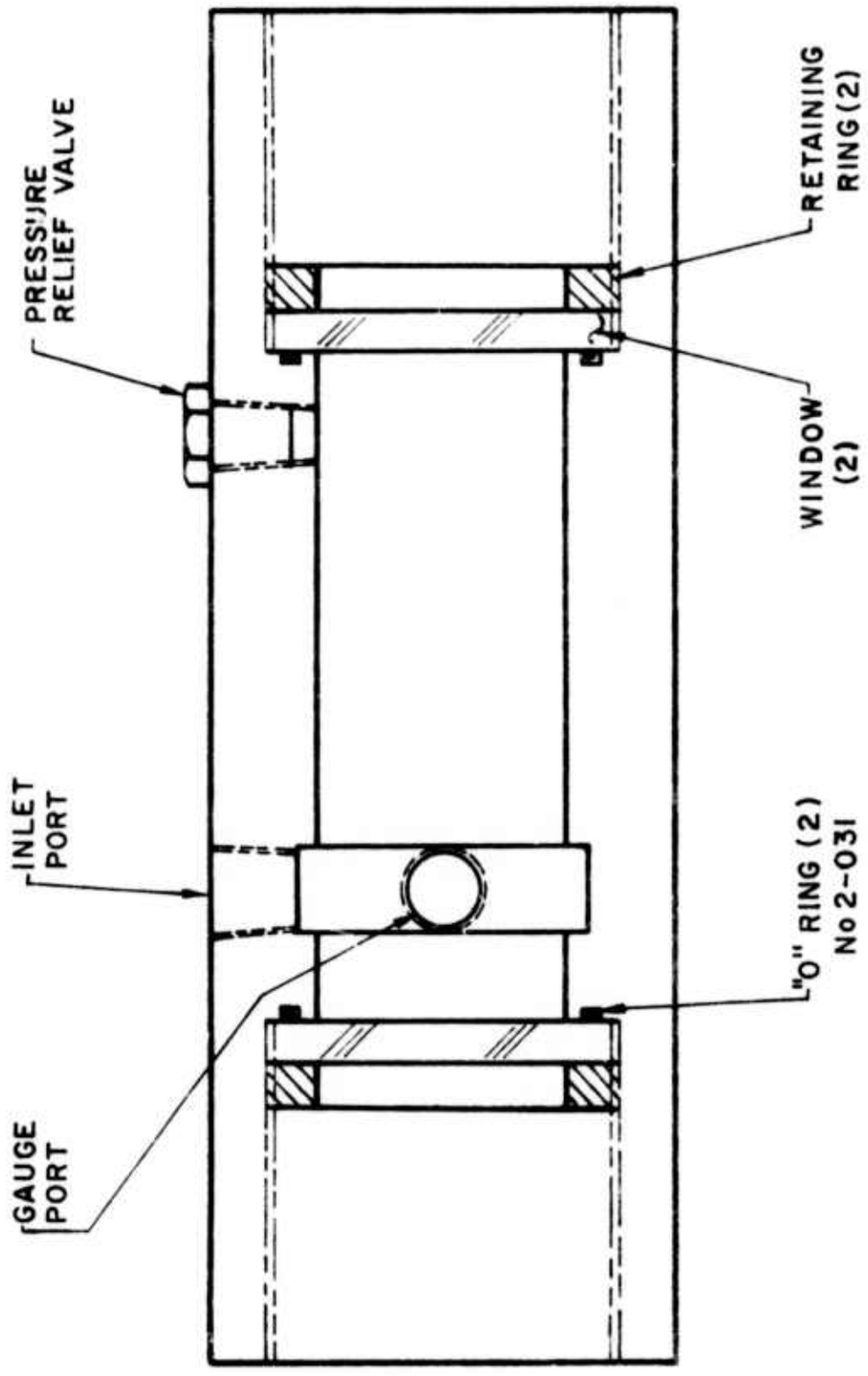

Figure 3. Gas Absorption Cell

SECTION V

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